LBNL-63698
MICE Note 193

# Quench Protection for the MICE Cooling Channel Coupling Magnet

**M. A. Green[a], L. Wang[b], X. L. Guo[b], F. Y. Xu[b], and L. X. Jia[b]**

**a) Lawrence Berkeley National Laboratory, Berkeley CA 94720, USA**
**b) Institute of Cryogenics and Superconductive Technology, HIT, Harbin, China**

**20 November 2007***

## Abstract

The MICE coupling coil is fabricated from Nb-Ti, which has high quench propagation velocities within the coil in all directions compared to coils fabricated with other superconductors such as niobium tin. The time for the MICE coupling coil to become fully normal through normal region propagation in the coil is shorter than the time needed for a safe quench (as defined by a hot-spot temperature that is less than 300 K). A MICE coupling coil quench was simulated using a code written at the Institute of Cryogenics and Superconductive Technology (ICST) at the Harbin Institute of Technology (HIT). This code simulates quench back from the mandrel as well as normal region propagation within the coil. The simulations included sub-division of the coil. Each sub-division has a back to back diodes and resistor across the coil. Current flows in the resistor when there is enough voltage across the coil to cause current to flow through the diodes in the forward direction. The effects of the number of coil sub-divisions and the value of the resistor across the sub-division on the quench were calculated with and without quench back. Sub-division of the coupling coil reduces the peak voltage to ground, the layer-to-layer voltage and the magnet hot-spot temperature. Quench back reduces the magnet hot-spot temperature, but the peak voltage to ground and layer-to-layer voltage are increased, because the magnet quenches faster. The resistance across the coil sub-division affects both the hot-spot temperature and the peak voltage to ground.

## TABLE OF CONTENTS



* Last revision 31 January 2008

## Introduction

The superconducting magnets in the MICE channel [1] may be connected to other coils of that in series. A quench of one magnet in the string will result in all magnets in the string being dumped [2]. If the other magnets in the string are not quenched through quench back, the stored magnetic energy in all of the magnets in the string will end up in the magnet that quenches. It is important that all of the magnets in MICE quench safely in a passive way. This report describes the passive quench protection system for the MICE coupling magnet that will be built at the Institute of Cryogenic and Superconductive Technology (ICST) [3].

There are two problems that are caused by the quenching of a superconducting magnet or a string of magnets. The first problem is the need to keep the temperature of the magnet hot spot (the place where the magnet quench started) below about 400 K. Excessive hot-spot temperatures will result in insulation failure and even a melting of the conductor. The second issue is the voltages developed turn-to-turn, layer-to-layer and coil-to-ground during the quench process. Excessive voltages can cause a voltage breakdown and arcing. An arc will direct the stored energy of the magnet to the place where it occurs and cause the coil to melt.

The two requirements of a magnet quench protection system (whether it be active or passive) are that the hot-spot temperature in the coil where the quench starts be no more than 350 to 400 K and that the turn-to-turn voltage be less than 50 V, the layer-to-layer voltage be less than 250 V, and that the voltage to ground be less than 1000 V. (In a potted magnet, the layer-layer voltage limit can be raised to 350 V and the voltage limit from the coil to ground can be raised to 2000 V. Conventional quench protection methods such as putting a resistor across the coil to extract the magnet energy can produce high voltages to ground when the hot-spot temperatures are made low. The most desirable way to protect the magnet is quench the entire coil quickly, so that the magnet stored-energy is put into the coils evenly. This has the effect of reducing the hot-spot temperature but this may increase the voltage to ground and the layer-to-layer voltage. The most desirable quench protection method for the MICE magnets is one that is completely passive. (A passive quench protection method does not need a quench detector, which in turn causes something to happen which caused the coil to quench safely.) Passive quench protection methods are inherently safe and are usually less expensive to implement, particularly in DC magnets.

The inductive coupling between a magnet and its mandrel can cause quench back [4] in the coil or any other coil in the string thus speeding up the quench process and thus reducing the hot-spot temperature of the coil that the quench starts in.

Magnet sub-division is a passive quench protection method long used in MRI magnets. Back-to-back diodes plus a resistance across the magnet sub-divisions passively protect the magnet. Back-to-back diodes allow the magnet to be safely quenched at either magnet polarity. The voltage forward direction across the diodes must be high enough to prevent current from bypassing the magnet coil during a magnet charge or discharge at its design charging and discharging voltages. Magnets that are protected using passive quench protection often require sub-division of the coil (or coils) to reduce the voltage between the coil and ground. Coil sub-division can also reduce the layer-to-layer voltage within the coil.

The primary reason that magnet sub-division is effective for quench protection of the coupling magnet (despite its large stored energy at full current) is that the time for the magnet to go completely normal is less than the current decay time constant needed for the magnet hot-spot temperature to be 300 K. Magnets made from A-15 or HTS conductor take longer to go completely normal. As a result, magnet sub-division alone may not be an effective way to passively protect such a magnet.

**Quench Propagation and Magnet Hot-spot Temperature**

For potted magnets fabricated using niobium titanium, the quench propagation velocity along the wire can be estimated using the following expression [5];

$$v \approx (5.7x10^{-14})(1+B)^{0.62} j^{1.65} \qquad \text{-1-}$$

where v is the quench propagation velocity along the wire; B is the magnetic induction at the wire; and j is the magnet current divided by the conductor cross-sectional area (excluding insulation). Note, equation 1 applies over a range for conductor current densities from $10^8$ to $5x10^8$ A $m^{-2}$ The primary reason the quench velocity is lower for niobium tin in that the enthalpy change to quench the niobium tin conductor is much higher.

Equation 1 applies for quench propagation velocity along the superconducting wire (in the θ direction in a solenoid). On can also estimate the quench propagation velocity in the other two directions using the following relationships;

$$v_R = \alpha v_\theta , \qquad \text{-2a-}$$

and

$$v_Z = \beta v_\theta . \qquad \text{-2b-}$$

$v_\theta$ is the velocity around the solenoid (in the direction of the wire); $v_R$ is the quench velocity in the radial direction in the solenoid; and $v_Z$ is the quench velocity along the length of the solenoid. The dimensionless function $\alpha = v_R/v_\theta$, and the dimensionless function $\beta = v_Z/v_\theta$.

The values of α and β depend on the dimensions of the bare conductor and the thickness of the insulation between layers (for α) and between turns (for β). The equations for calculating α and β for the MICE solenoid coils are as follows [4];

$$\alpha \approx 0.7\left[\frac{\rho_n k_i}{LT_c}\frac{b}{S}\frac{r+1}{r}\right]^{0.5}, \qquad \text{-3a-}$$

and

$$\beta \approx 0.7\left[\frac{\rho_n k_i}{LT_c}\frac{a}{S}\frac{r+1}{r}\right]^{0.5}. \qquad \text{-3b-}$$

In equations 3a and 3b, L is the Lorentz number ($L = 2.45x10^{-8}$ $\Omega WK^{-2}$.); $k_i$ is the thermal conductivity of the insulation material (For a potted magnet, $k_i = 0.04$ $Wm^{-1}K^{-1}$.); $T_c$ is the conductor critical temperature (use 7 K for Nb-Ti); and $\rho_n$ is the resistivity of the matrix metal. (For copper, $\rho_n = 1.55x10^{-8}$/RRR in Ω m.) (Note: RRR is the ratio of the normal metal resistivity at 273 K to the normal metal resistivity at 4 K.) The values of α and β are inversely proportional to the square root of RRR. S is the insulation thickness; a is the length of the conductor (in the z direction); b is the thickness of the conductor (in the r direction); and r is the copper to superconductor ratio. In general, α and β will have a value of 0.012 to 0.05 for a typical niobium titanium magnet with a copper matrix superconductor with an RRR from 20 to 140. It is well understood that RRR has almost no effect on the quench velocity along the wire. RRR does affect the turn-to-turn and layer-to-layer propagation velocity within a coil. To first order, the turn-to-turn and layer-to-layer quench propagation velocity is proportional to $(RRR)^{-0.5}$.

The limit for the burnout condition for a superconducting magnet is derived by integrating the following equation [5] [6];

$$F = \int_0^t j^2 dt . \qquad \text{-4-}$$

Redefining this equation slightly from the basic definition for F*(T) can be derived;

$$F^*(T) = \int_0^T \frac{C(T)}{\rho(T)} dT = \frac{r+1}{r} \int_0^t j^2 dt . \qquad \text{-5-}$$

When a magnet quenches the start for the quench is t = 0. The end at time for the magnet quench is when the current in the coil has completely decayed away $t = \infty$. Using the quench time limits, the equation for F*(T) takes the following form;

$$F^*(T_M) = \int_0^{T_M} \frac{C(T)}{\rho(T)} dT = \frac{r+1}{r} \int_0^\infty j^2 dt = \frac{r+1}{r} J_0^{\,2} \int_0^\infty \Xi(t)^2 dt \qquad \text{-6-}$$

The temperature $T_M$ is the maximum hot-spot temperature in the coil. $J_0$ is the starting current density in conductor cross-section and $\Xi(t)$ is the decay function for the current in the magnet with time ($\Xi(0) = 1$; $\Xi(\infty) = 0$). Figure 1 Shows F*(T) as a function of temperature T and the matrix material RRR. Figure 1 shows this for both copper matrix conductors and aluminum matrix conductor. The lower values of F*(T) for aluminum conductors reflect the lower volume specific heat and higher resistivity for the matrix at a given RRR.

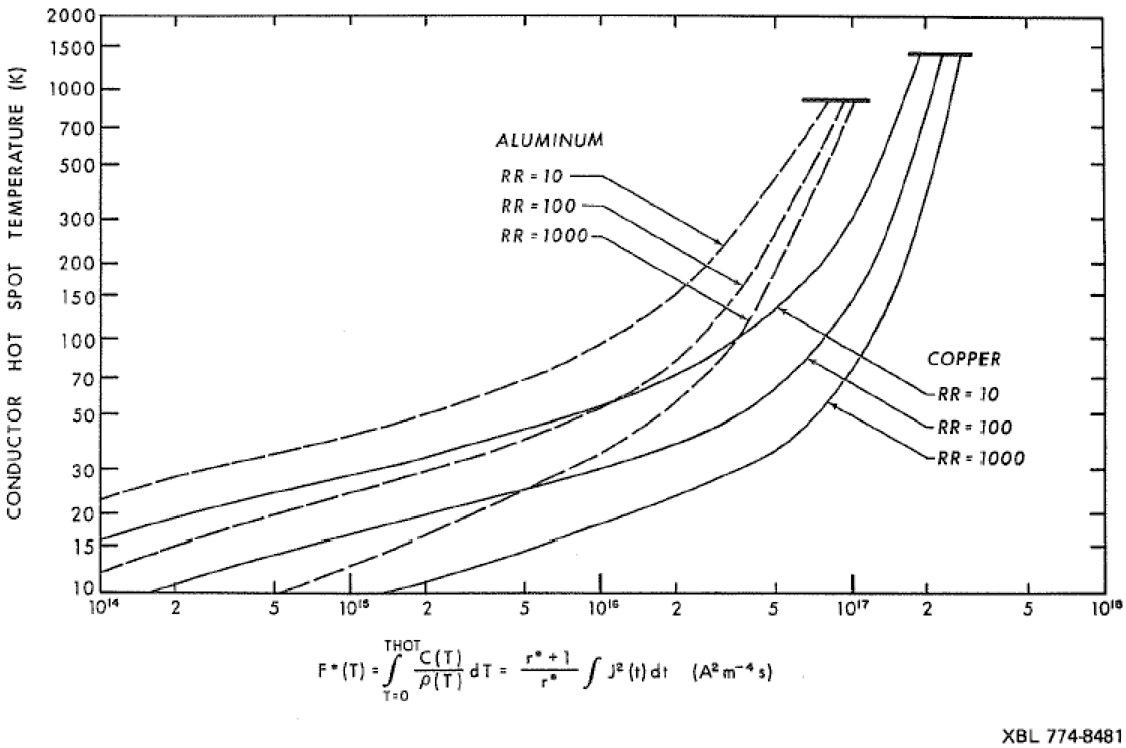



**Figure 1**. Hot-spot Temperature $T_M$ versus F*(T) for Copper and Aluminum with Various RRR Values

The $L/R(T_M)$ time constant for a given hot-spot temperature $T_M$ (say 300 K) can be calculated for a magnet using the following expression [5], [7];

$$\frac{L_1}{R_1}(T_M) = \frac{2F^*(T_M)}{j_0^2}\frac{r}{r+1} \qquad \text{-7-}$$

where $L_1$ is the self-inductance of the coil (see Figure 1); $R_1$ is the quench resistance; $j_0$ is the conductor (matrix plus superconductor) current density; r is the copper to non-copper ratio; and $F^*(T_M)$ is defined by equations 6.

## How Sub-division works to protect a Superconducting Magnet

The key equation for explaining how magnet sub-division works as a method of magnet quench protection is as follows [5], [7];

$$E_o j_o^2 = F^*(T_M) V_o i_o \frac{r}{r+1} \qquad \text{-8-}$$

where $E_o$ is the fully charged stored energy of the magnet (at the start of the quench); $j_o$ is the current density across the conductor cross-section (copper plus superconductor). $F^*(T_M)$ and r are previously defined. The quench $Ej^2$ function is proportional to $F^*(T_M)$, the maximum discharge voltage $V_o$ and the starting current $I_o$.

From equation 8, it is clear that magnets with high currents are easier to protect during a quench than coils with low currents. One typically wants to limit the peak voltage within the magnet coil. Sub-division of the coil divides the coil into cells. Each of the cells has a lower stored energy. For example, if the coil stored-energy is 12.8 MJ, one can reduce the cell stored energy to 3.2 MJ by dividing the coil into four parts as shown in Figure 2 below.

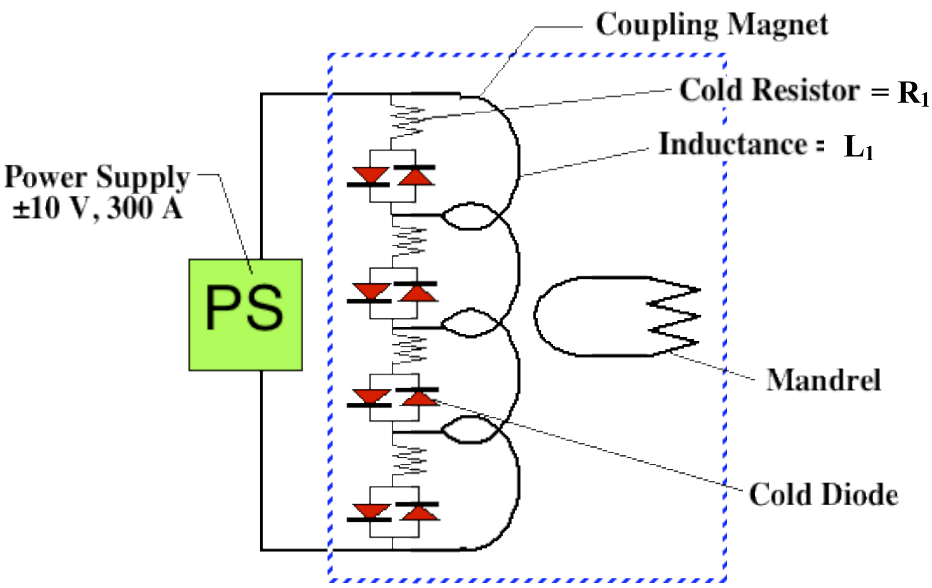



**Figure 2.** Quench Protection using Sub-division of a Superconducting Coil using Cold Diodes and Resistors

Figure 2 shows back-to-back diodes and a resistor in parallel with the coil sub-division. At 4 K the diodes have a forward voltage drop of about 4 volts. The back-to-back diodes in parallel with the resistor allow the magnet to operate at either polarity. Energy is dissipated in the resistor and the diode. As the diode heats up its forward voltage drop goes down.

If one looks at equation 8 for the MICE coupling magnet with a stored energy at full current E = 12.8 MJ, $i_0$ = 210 A, j = $1.5 \times 10^8$ A $m^{-2}$, r = 4, and F*(300 K) = $1.5 \times 10^{17}$ $A^2$ $m^{-4}$ s, the quench voltage across the coil must be about 11430 V. Table 1 presents quench parameters for two versions of the coupling coil with design currents of 210 A and 277 A.

**Table 1.** A Comparison of the Quench Characteristics of Two Versions of the MICE Coupling Magnet

| Parameter | Version 1 | Version 2 |
|---|---|---|
| Conductor Current Density (A $mm^{-2}$) | 150 | 150 |
| Longitudinal Quench Velocity (m $s^{-1}$) | 3.49 | 3.49 |
| Time for a Natural Magnet Coil Quench (s) | ~4.1 | ~4.0 |
| Magnet Design Current $I_D$ (A) | 210 | 277 |
| Magnet Self Inductance (H) | ~580 | ~330 |
| Magnet Stored Energy at $I_D$ (MJ) | 12.8 | 12.8 |
| L/R Time Constant for $T_M$ =300 K (s) | 10.7 | 10.7 |
| $EJ^2$ for Magnet at $I_D$ (J $A^2$ $m^{-4}$) | $2.88 \times 10^{23}$ | $2.88 \times 10^{23}$ |
| Copper to Superconductor Ratio r | 4 | 4 |
| Discharge Voltage for the above L/R (V) | 11430 | 8670 |
| Number of Magnet Sub-divisions | 8 | 6 |

If one sub-divides the coil and puts a resistor across each sub-division as shown in Figure 2, the voltage across each sub-division will be less than 2.9 kV for an L/R time constant of 10.7 seconds. The design voltage across each sub-division should be less than 2500 V. Furthermore, it is desirable to sub-divide the coil in even sub-divisions (4, 6, 8, and so on). The numbers of sub-divisions in Table 1 reflect the desire to have and even number of sub-divisions and wanting a voltage across each sub-division less than 2500 V.

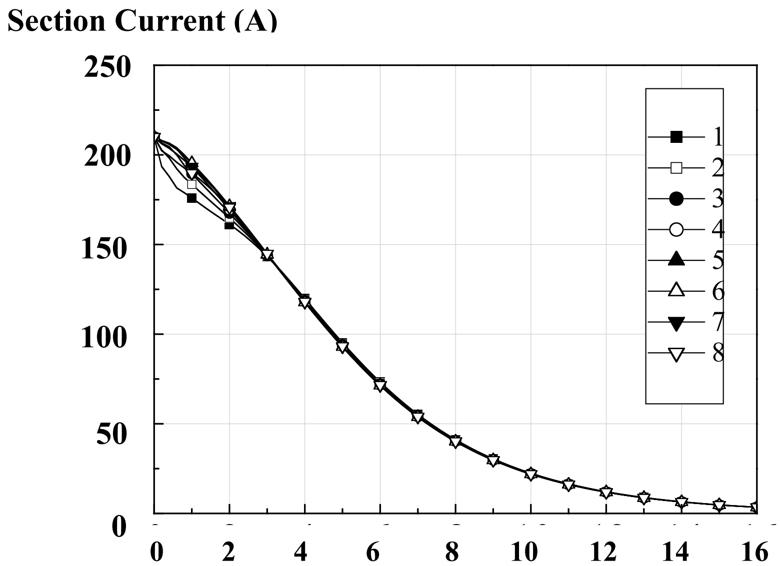



**Figure 3**. The Current in Each Magnet Section as a Function of Time during a Quench of Magnet with Eight Sub-divisions with Quench-back and R = 5 ohms (Note: The quench time constant is ~6 seconds.)

Figure 3 shows the current in each magnet section as a function of time after the start of a quench in the inner surface of the inner magnet section (section 1) at its center. The magnet sections are numbered on through 8 as one goes out from the mandrel. Since the magnet used for the simulation has 96 layers, each magnet sub-division has 12 layers. The case shown in Figure 3 is one where the resistor across the coil is 5 ohms. There is quench-back from the mandrel to the coils.

It is interesting to note that the time constant for the magnet quench decay is ~6 sec. This time constant is longer than the time for the coil to go normal (~4 sec.). The quench time constant is shorter than the current decay time constant that leads to an F* for a hot-spot temperature of 300 K. When one looks at the coil current decay data given in Figure 3, it is clear that the hot-spot temperature for the magnet quench must be less than 300 K.

The current decay at the beginning of the quench is rapid in section 1, which is the section where the quench started. Current is shifted from the coil to the resistor. Flux is conserved, so a reduction in the current in the inner section (section 1) caused the current to increase in the outer sections. This current increase is particularly apparent in sections 6, 7, and 8. In fact, the current in all of the magnet sections is higher early in the quench than it is in section 1. The divergence of the currents in the coil sections continues to about t = 1 s. At this point the current in the various magnet sections begins to converge. At t = 3 s, the currents in all of the magnet sections are nearly equal. At this point the whole magnet is normal and the stored energy is being put into all of the coil sections more or less equally.

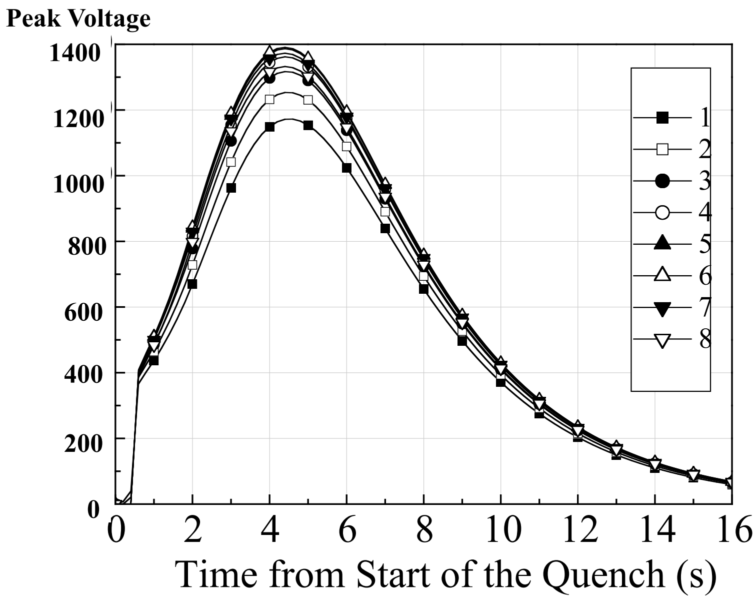



**Figure 4**. The Voltage to Ground in Each Magnet Section as a Function of Time during a Quench of Magnet with Eight Sub-divisions with Quench-back and R = 5 ohms

Figure 4 shows the current in each magnet section as a function of time after the start of a quench in the inner surface of the inner magnet section (section 1) at its center. The magnet sections are numbered on through 8 as one goes out from the mandrel. The case shown in Figure 4 is one where the resistor across the coil is 5 ohms. There is quench-back from the mandrel to the coils. From Figure 4, it is clear that the peak voltage does not occur in the section where the quench occurred (section 1). The peak voltage occurs in section 6 at a time of about 5.5 seconds. It appears that the peak voltage in magnet section 6 is caused by a combination of the di/dt in the section and the resistance of the section 6.

Figure 5 shows the hot-spot temperature in each section as a function of time after the start of a quench at the center of the inner surface of the inner magnet section (section 1). According to Figure 5, the peak hot-spot temperature occurs in the sixth section, which is about 70 percent of the distance out in the coupling coil.

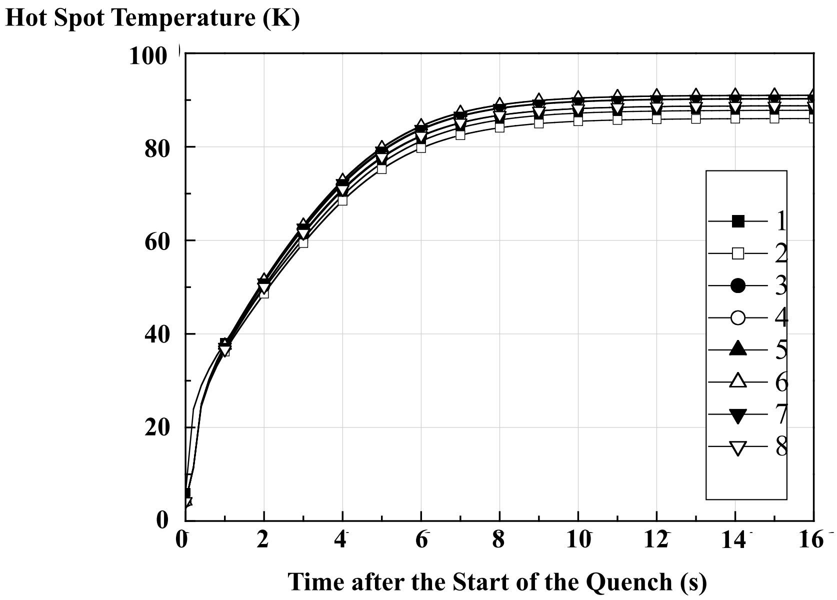



**Figure 5**. The Peak Hot-spot Temperature in Each Magnet Section as a Function of Time during a Quench of Magnet with Eight Sub-divisions with Quench-back and R = 5 ohms

In Figure 5, it appears that the lowest hot-spot temperature occurs in section 2. The hot-spot temperature in section 1 is probably very close to that in section 6. The hot-spot line for section 1 is either missing or behind one of the other lines. The hot-spot temperature appears to about 90 K. The reason for this may be that the sixth section carried more current, because it was coupled with the inner sections of the coil that went normal sooner. Section 6 also has the highest voltage to ground. (See Figure 4 and Table 2.)

It is important to remember that each coil sub-division is inductively coupled to every other coil sub-division. The magnet aluminum mandrel is also inductively coupled to all of the coil sub-divisions. The mandrel carries a portion of the magnet current as the magnet quenches. The current in the mandrel will heat the mandrel, which will eventually heat up the adjacent coil sections. This process is called quench back [6]. Quench back will speed up the quench process. Sub-division of the coil reduces the hot-spot temperature, because the resistor carries part of the current flowing through the conductor hot spot and the same resistor diverts some of the current in a coil section to other coil sections by inductive coupling. Sub-division of the coil reduces the peak voltages to ground within the coil. At worst, the voltage to ground will go down as the number of sub-divisions. The studies at ICST suggest that coil sub-division can reduce the voltages within the coils by more than one over the number of coil sub-divisions. As a result, layer-to-layer voltages will also go down.

It is always interesting to note where the quench energy ends up at the end of the quench. The total coil stored energy is 12.8 MJ. At the end of the quench, about 6.8 MJ ends up in the superconducting coil (predominantly copper), about 0.4 MJ ends up in the aluminum mandrel, cover plate and cooling tubes and 5.6 MJ ends up in the resistance outside the magnet. The average magnet temperature will be about 72 K. The 5-ohm resistor absorbs nearly half the magnet energy, which results in a lower magnet hot spot temperature.

## The Effect of Coil Sub-division, Conductor Size, By-pass Resistance and Quench Back on MICE Coupling Magnet Quenches

Tables 2 and 3 below show the effect of subdivision of the MICE coupling magnet on the quench protection of a magnet coil that has an average diameter of 1590 mm, a coil length of 285 mm and a coil thickness of 102 mm. In both tables, the magnet is charged to its peak operating current with a total of 3.348 MA turns. The magnet in Table 2 has the small conductor ($I_o$ = 210.1 A). Table 3 is for a magnet with a large conductor ($I_o$ = 276.2 A).

**Table 2.** MICE Coupling Coil Quench Characteristics with Small Conductor (1.00 mm x 1.65 mm insulated)

| Parameter | | w Quench Back | | w/o Quench Back | |
|---|---|---|---|---|---|
| | | R = 5Ω | R = 0 | R = 5Ω | R = 0 |
| 1 Coil | Peak Voltage (V) Location | 22746/1 | 22746/1 | 22746/1 | 22746/1 |
| | Hot-spot Temperature (K) Location | 166/1 | 166/1 | 175/1 | 175/1 |
| 2-subs | Peak Voltage (V)/Location | 8845/2 | 10546/2 | 9331/2 | 11373/2 |
| | Hot-spot Temperature (K) /Location | 129/1 | 148/1 | 138/1 | 150/1 |
| 4-subs | Peak Voltage (V) /Location | 3818/3 | 5331/3 | 3834/3 | 5750/3 |
| | Hot-spot Temperature (K) /Location | 107/1 | 139/1 | 119/1 | 141/1 |
| 6-subs | Peak Voltage (V) /Location | 2168/4 | 3558/4 | 2065/4 | 3837/4 |
| | Hot-spot Temperature (K) /Location | 96/1 | 136/1 | 106/1 | 139/1 |
| 8-subs | Peak Voltage (V) /Location | 1391/6 | 2669/5 | 1251/6 | 2878/5 |
| | Hot-spot Temperature (K) /Location | 88/1 | 134/5 | 95/5 | 137/5 |

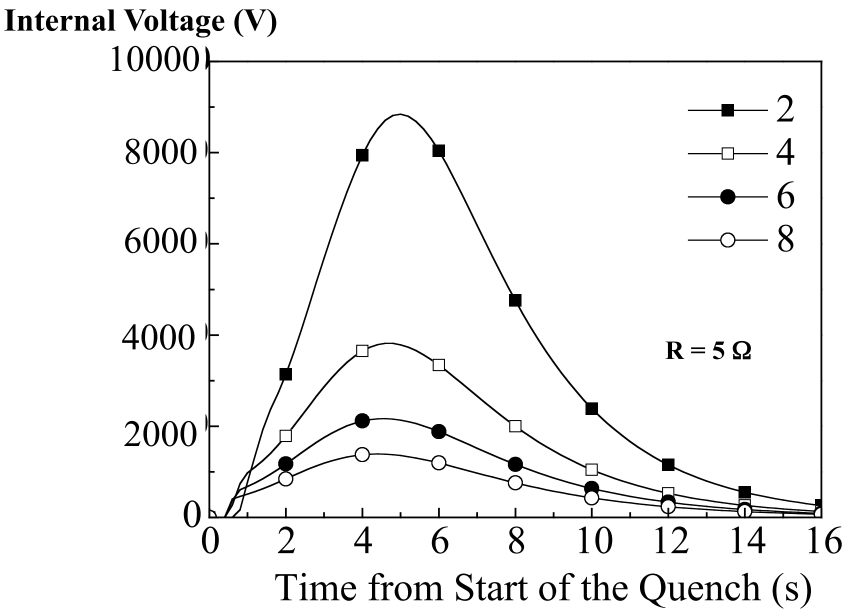
* Location is number of the coil in which the peak voltage or the hot-spot temperature occurs.

**Table 3.** MICE Coupling Coil Quench Characteristics with Large Conductor (1.15 mm x 1.90 mm insulated)

| Parameter | | w Quench Back | | w/o Quench Back | |
|---|---|---|---|---|---|
| | | R = 5Ω | R = 0 | R = 5Ω | R = 0 |
| 1 Coil | Peak Voltage (V) Location | 16790/1 | 16790/1 | 16790/1 | 16790/1 |
| | Hot-spot Temperature (K) Location | 145/1 | 170/1 | 152/1 | 173/1 |
| 2-subs | Peak Voltage (V)/Location | 5742/2 | 7793/2 | 5893/2 | 8395/2 |
| | Hot-spot Temperature (K) /Location | 116/1 | 145/1 | 128/1 | 148/1 |
| 4-subs | Peak Voltage (V) /Location | 2181/3 | 3938/3 | 2049/3 | 4242/3 |
| | Hot-spot Temperature (K) /Location | 94/1 | 137/1 | 103/1 | 140/1 |
| 6-subs | Peak Voltage (V) /Location | 1106/4 | 2628/4 | 945/4 | 2830/4 |
| | Hot-spot Temperature (K) /Location | 80/1 | 135/1 | 87/2 | 137/1 |
| 8-subs | Peak Voltage (V) /Location | 724/6 | 2064/5 | 566/5 | 2222/5 |
| | Hot-spot Temperature (K) /Location | 72/6 | 133/1 | 77/5 | 136/1 |

* Location is number of the coil in which the peak voltage or the hot-spot temperature occurs.

Tables 2 and 3 show the peak internal voltage and the sub-division where that peak voltage occurs for the MICE coupling magnet. The tables also show the peak magnet hot-spot temperature and the subdivision where that peak hot-spot temperature occurs. Figure 3 shows the internal voltage and hot-spot temperature for the sub-division with the highest value as a function of the time from the start of the quench and the number of sub-divisions. The upper part of Figure 6 is a plot of peak internal voltage as a function of time from the start of the magnet quench and number of magnet divisions. The lower part of Figure 6 is a plot of peak hot-spot temperature as a function of the time after the start of the magnet quench and the number of magnet divisions. Figure 6 applies for the coupling magnet made from the small conductor, with quench back considered, and a 5-ohm division resistance.



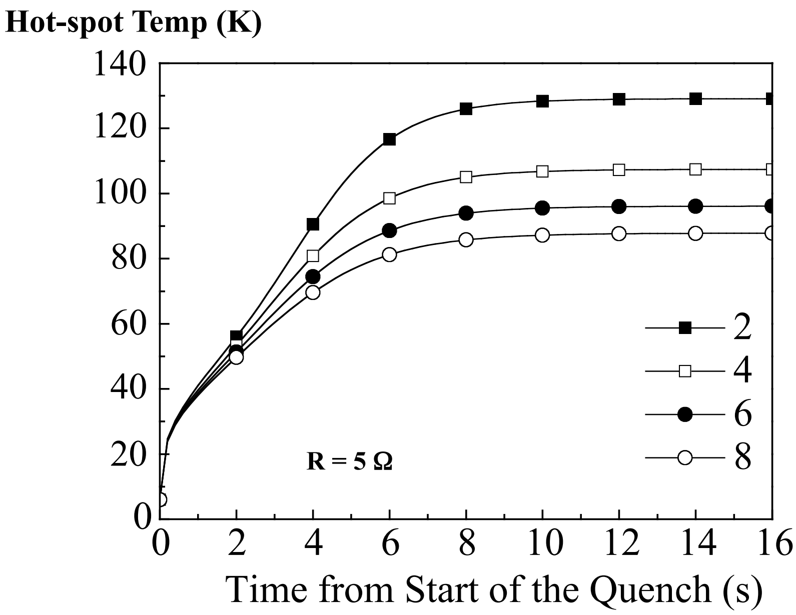




**Figure. 6** Magnet Internal Voltage (upper graph) and Magnet Hot-spot Temperature (lower graph) Versus the Time after the Quench Start for the MCE Coupling Coil using the Small Conductor with Quench Back

Tables 2 and 3 show the effects of the conductor size (magnet current), the number of magnet sub-divisions, the resistance of the by-pass resistor, and quench back. It is clear from the tables that subdivision reduces both the internal voltages within the coil, the coil hot-spot temperature during the magnet quench, and perhaps the layer-to-layer voltage. The effect of the resistance put in parallel with the coil section is also quite evident. Figures 7 and 8 show plots of peak internal voltage and peak hotspot temperature versus the number of divisions. For both Figure 7 and Figure 8 there is R = 5 ohms with quench back (S5QB); R = 0 with quench back (S0QB), R = 5 ohms without quench back (S5NQB), and R = 0 without quench back (S5NQB).

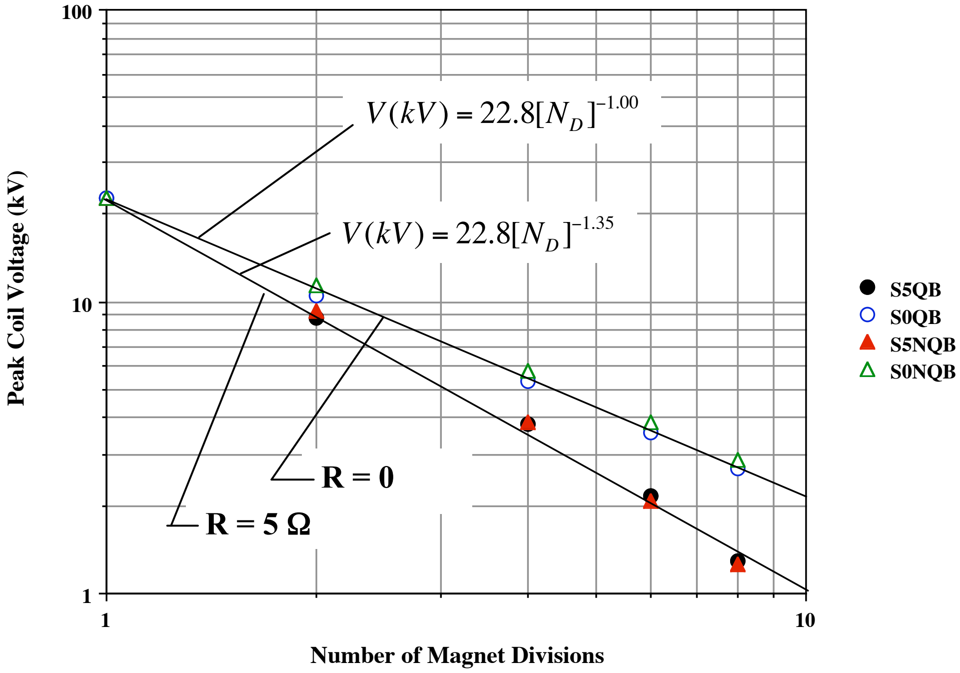



**Figure 7**. The Peak Internal Voltage versus Number of Magnet Divisions as a Function of the of the Resistance across the Division for Cases with and without Quench-back using the Small Conductor

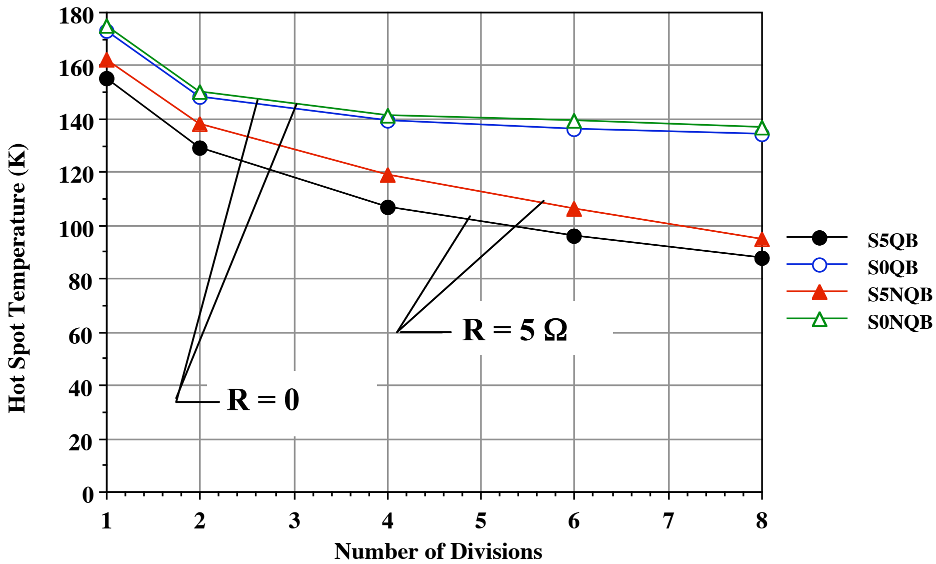



**Figure 8**. The Magnet Hot-spot Temperature versus Number of Magnet Divisions as a Function of the Resistance across the Division for Cases with and without Quench-back using the Small Conductor

Figure 8 shows the effect of the number of sub-divisions, the resistance across each division, and quench-back on the peak internal voltage within the magnet. When the resistance across the sub-divisions is zero, the peak internal voltage is proportional to one over the number of subdivisions. The peak layer-to-layer voltage is equal to two times the peak internal voltage divided by the number of layers in that sub-division. When the resistance across the sub-division is zero, the layer-to layer voltage does not change with number of sub-divisions. When there is a resistance across the sub-division (a diode is enough), the peak internal voltage drops faster than one over the number of sub-divisions. Thus when there is a resistance across the sub-division, the layer-to-layer voltage goes down as the number of magnet sub-divisions increases.

When one has a 5 ohm resistor across each sub-division the, peak voltage goes down as $N_D^{-1.35}$. (See Figure 7) The reason the resistance goes down faster is that a 5 ohm resistor is put across each subdivision. Thus more energy is removed from the coil and put into the shunt resistors. If the resistance across each sub-division were reduced to say 2.5 ohms, one would expect the peak voltage to go down as $N_D^{-1.18}$. If the resistance across the coil subdivision were perfectly optimized, the peak voltage would go down as $N_D^{-1.41}$. Unfortunately, it is difficult to optimize the resistance across the coil and it is also difficult to put a resistor in the shunt circuit that won't overheat when the magnet is quenched.

The magnet hot-spot temperature goes down as the resistance across the coil increases. The reason for this is that the shunt resistor absorbs magnetic energy from the magnet. This energy does not end up in the quench hot spot. More magnet sub-divisions means that more energy is removed from the superconducting coils and the hot-spot.

### The Low Resistance (R = 0) Case is More Typical for a Sub-divided Magnet

It is clear that it is desirable to have a large resistance across each sub-division. It turns out the R = 5 ohms is nearly optimum because close to half of the magnet stored energy ends up in the by-pass resistors and diodes. In order to use 5-ohm resistors, these resistors must have enough mass to absorb the magnet energy and keep their temperature at 300 K or below. If the coupling magnet resistor temperature is 300 K at the end of the quench, the mass of each resistor must be about 10 kg for each sub-division. If one wants the coupling magnet resistor temperature to end up at 200 K, the mass of each resistor must be about 20 kg.

Most magnets that are protected by sub-division have almost no resistance across the sub-division accept that provided by the diode. When the resistance across the subdivision is zero, the about 12.3 MJ will end up in the coil and 0.5 MJ will end up in the mandrel. For the case where the resistance across the sub-divisions is zero, the average magnet temperature is about 92 K. When one looks at the R = 0 eight sub-division case in Table 2 and Figure 8 sees that the hot-spot temperature is about 135 K versus a hot-spot temperature of 90 to 95 K for the case where the shunt resistance is 5 ohms.

The MICE coupling coil has very little space for resistors with enough mass to prevent them from getting too hot during a quench. The MICE coupling coil magnet has a resistance of about 8 m-ohms in the shunt resistance. The resistors are quite small with a mass of about 30 grams each. The effect of the diode has been neglected in the analysis given in this report. The diode in fact does have resistance. At 4 K the resistance of the diode in the forward direction while it is carrying 100 A will be about 50 m-ohms. As the diode heats up, it forward voltage goes down. At room temperature the diode resistance will be about 8 m-ohm when it carries 100 A in the forward direction. The diode resistance must be added to the shunt resistance. As a result, the one can expect about 0.03 to 0.05 MJ to be deposited in the diode and resistors for the MICE coupling magnet. This energy is small.

### Concluding Comments

During a magnet quench, sub-division of a magnet into sections reduces the peak voltage to ground within the magnet. The reduction in the voltage to ground appears to be greater when there is a resistance in the circuit that bypasses the magnet sections. Quench-back appears to have only a small effect on the peak voltage to ground within a magnet.

During a quench of a sub-divided magnet, current will be distributed differently in various magnet sections, because there is inductive coupling between the magnet sections. As a result, the hot-spot temperature in the magnet coil will be reduced by magnet sub-division. Quench-back from the magnet mandrel appears to reduce the magnet hot-spot temperature further.

The use of a 5-ohm resistors across each sub-division reduces the internal voltage, the layer to layer voltage and the hot-spot temperature. In reality, the MICE coupling coil will have a very low resistance across each sub-division. This resistance is about 25 m-ohm (including the diodes). The internal voltages within the magnet increase about a factor of two when the shunt resistance is in the 25 m-ohm range. The hot-spot temperature will be about 135 K, which is entirely acceptable in the coupling magnet.

No active external quench protection system is needed for the MICE coupling magnet. Sub-division of the magnet alone will reduce the voltages to ground to an acceptable level and at the same time reduce the magnet hot-spot temperature. Increasing the resistance across the magnet sub-section appears to reduce the voltage to ground within magnet sections. The resistance also reduces the layer-to-layer voltage within the magnet.

## Acknowledgements

This work was supported by the Harbin Institute of Technology through funding to the Institute of Cryogenic and Superconductive Technology. This work was also supported by the Lawrence Berkeley Laboratory and the Office of Science, United States Department of Energy, under the DOE contract DE-AC03-76SF00098.

## References

[1] G. Gregoire, G. Ryckewaert, L. Chevalier, et al, “MICE and International Muon Ionization Cooling Experiment Technical Reference Document,”(October 2004)

[2] S. Q Yang, D. E. Baynham, P. Fabricatore, et al, “The Physical Connection and Magnetic Coupling of the MICE Cooling Channel Magnets and the Magnet Forces for Various MICE Operating Modes,” *IEEE Transactions on Applied Superconductivity* **17**, No. 2, p (2007)

[3] L. Wang, M. A. Green, F. Y. Xu, H. Wu, et al, “The Engineering Design of the 1.5 meter Diameter Solenoid for the MICE RFCC Modules,” to be published in *IEEE Transactions on Applied Superconductivity* **18**, No. 2, (2008)

[4] M. A. Green, "The Role of Quench Back in Quench Protection of a Superconducting Solenoid", *Cryogenics* **24**, p 659, (December 1984).

[5] M. A. Green and H. Witte, “Quench Protection and Power Supply Requirements for the MICE Focusing and Coupling Magnets,” LBNL-57580, MICE Note 114, (2005)

[6] W. H. Cherry and J. I Gittlemen, “Thermal and Electrodynamic Aspects of the Superconductive Transition Process,” *Solid State Electronics* **1**, p 287 (1960)

[7] M. A. Green, P. H. Eberhard, M. Alston-Garnjost, et al, "Quenches in Large Superconducting Magnets", *Proceedings of the 6th International Conference on Magnet Technology* **6**, Bratislava, Czechoslovakia, p 654, LBL-6718, August 1977.

**DISCLAIMER**